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Development of a spherical tissue equivalent proportional counter for neutron monitoring*

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A spherical tissue equivalent proportional counter (TEPC) for neutron monitoring has been developed. It was properly designed to produce a uniform electric field intensity around the anode wire. An internal ^{241}Am alpha source was adopted for lineal energy calibration. The TEPC was characterized in terms of dose equivalent response in a standard ^{252}Cf neutron field, and was tested with 2.45 MeV neutrons. Microdosimetric spectra, frequency mean lineal energy and dose-average mean lineal energy of 2.45 MeV neutrons were obtained and compared with FLUKA Monte Carlo simulation results. The measurement and simulation results agreed well. The mean quality factor and dose equivalent values evaluated from the 2.45 MeV neutron measurement were in good agreement with the recommended effective quality factor and ambient dose equivalent $H^*(10)$, respectively. Preliminary results have proved the availability of the developed TEPC for neutron monitoring.

Keywords: Neutron monitoring, Tissue-equivalent proportional counters, Dose equivalent response, FLUKA simulation, Microdosimetric spectra, Mean quality factor

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I. INTRODUCTION

Tissue-equivalent proportional counters (TEPC) are widely used in radiation protection and radiation biology [1]. In neutron monitoring, real-time dosimeters are vital for radiation protection. Most of them are of the type with a thermal neutron detector inside a large polyethylene sphere [2–4]. These moderator-based instruments convert their response to dose equivalent by simple calibration in a reference neutron spectrum, which is assumed to be valid for other fields. It is obvious that such neutron dosimeters are applicable to limited situations, and may give rise to large errors sometimes [5]. Besides, such a dosimeter is usually too heavy to handle [6].

Unlike traditional dosimeters, the application of low pressure TEPCs in neutron radiation protection is based on simultaneous measurement of absorbed dose D and mean quality factor $\bar{Q}$. The dose equivalent H is calculated by Eqs. (1)–(3) [7–9],

$$H = D \times \bar{Q}, \tag{1}$$

$$D = \frac{0.204}{d^2}\sum_{i=1}^{N} y_i \times n(y_i), \tag{2}$$

$$\bar{Q} = \frac{\sum_{i=1}^{N} Q(y_i) \times y \times f(y_i)}{\sum_{i=1}^{N} \times f(y_i)}, \tag{3}$$

where, y is lineal energy defined as the quotient of energy imparted ε, to the matter in a volume from a single energy deposition event by a mean chord length $\bar{l}$ in that volume [9] ($\bar{l} = 2/3$ µm for a spherical cavity being equivalent to a tissue cell of Φ1 µm); d (in µm) is inner diameter of the TEPC, $n(y_i)$ is the number of counts within the interval y_i ; $Q(y)$ is the quality factor defined as a function of linear energy transfer (LET) recommended in International Commission on Radiological Protection 60 report [10]; and $f(y)$ is the probability density function of the lineal energy y.

Consequently, TEPCs are promising candidates for neutron radiation protection. In this work, a spherical TEPC was developed. The prototype detector was characterized by a built-in ^{241}Am alpha source and a standard ^{252}Cf field. The TEPC was characterized with 2.45 MeV neutrons, and its performance was satisfactory.

II. EXPERIMENTS

A. Detector configuration

Benjamin design [11, 12] is employed in the spherical TEPC to keep multiplication process spatially uniform around the anode wire. Figure 1 shows a sketch and picture of the TEPC. With an inner diameter of 44.8 mm, the TEPC is made of A-150 (Shonka [13]) plastic in wall thickness of 3.0 mm. A single tungsten wire (Φ25 µm, gold-coated) is used as the anode. An outer stainless steel shell of 3.0 mm thickness is used for air tightness. Sealed mode, instead of gas-flow system, was employed for portability consideration. Leak rate of the system was measured at $< 10^{-13}$ Pa m^3/s, ensuring working stability of the TEPC. An ^{241}Am alpha source is attached to the outside wall for energy calibration. Most of the alpha particles can go into the cavity through a Φ1 mm hole on the cathode wall. In this work, the TEPC was temporarily flushed with methane based tissue equivalent (MTE) gas (64.4% CH_4, 32.4% CO_2, 3.2% N_2) of 2.12 kPa to simulate soft tissue of 1 µm size, that is, the deposited energies by a charged particle along the TEPC diameter are equivalent to the absorbed energies in soft tissue of 1 µm size. An absolute barometer was used to measure MTE gas pressure of the detector, from 0 to 100 kPa, with the precision of 0.01 kPa.

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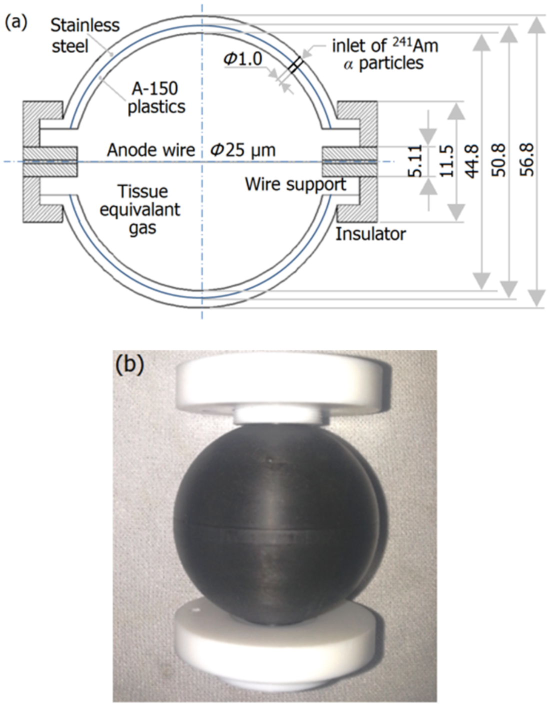

Fig. 1. (Color online) The sketch (a) and picture (b) of the TEPC detector.

B. Experiments in reference ^{252}Cf field

Dose equivalent response R_H is defined as the ratio of dose equivalent reading of a TEPC to the ambient dose equivalent H*(10) [14] at the same point. R_H of the TEPC was measured in a standard bare ^{252}Cf neutron radiation field. Neutron emission rate of the ^{252}Cf source is about $4.86 \times 10^6\ \mathrm{s}^{-1}$. In this measurement, the TEPC was tested with the electronic system in Fig. 2. The detector pre-amplifier (ORTEC 142PC) was set in irradiation room and the TEPC was placed 30 cm away from the ^{252}Cf source. A 40-m signal cable connecting the pre-amplifier and amplifier brought significant noise to the measuring system. This noise was measured after the experiment and subtracted from the measured neutron pulse height distribution.

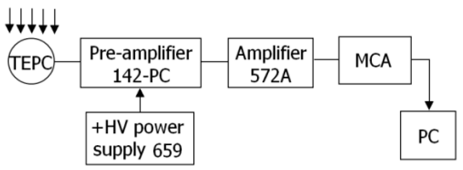

Fig. 2. Experimental circuit in ^{252}Cf reference field.

C. Measurements in mono-energy neutron field

The TEPC was tested with 2.45 MeV neutrons generated by $d(d,n)p$ reaction. A schematic layout of the experimental arrangement was shown in Fig. 3. Deuterium ions were accelerated to bombard deuterium target to produce 2.45 MeV neutrons. The TEPC detector was placed at 20 cm from the target. A Si(Au) surface barrier detector (SBD) was used to monitor total neutron yields by recording the protons at 135° to the beam incidence and at 1 m from the target. It is assumed that contamination of the photo events for an accelerator-based neutron source are negligible.

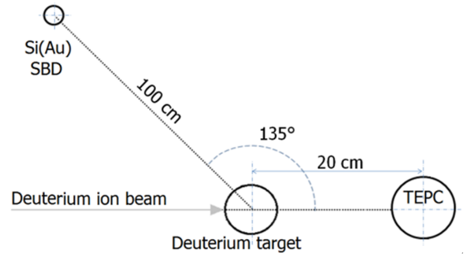

Fig. 3. Experimental arrangement of mono-energetic neutron measurement.

III. RESULTS AND DISCUSSION

A. Characterization of the TEPC with built-in ^{241}Am alpha source

Calibration of the TEPC was implemented with an ^{241}Am alpha source. Because of the extremely low pressure of MTE gas in the TEPC, the alpha particles lose only part of its kinetic energy in the gas cavity. A typical signal of ^{241}Am alpha source output from pre-amplifier (142-PC) is shown in Fig. 4. Energy deposition of 5.48 MeV alpha particles of ^{241}Am in the gas cavity was simulated by FLUKA codes [15]. In the simulation, the sampling alpha particles were set to fire into the TEPC along the cavity diameter. The result of energy deposition distribution was plotted in Fig. 5. It can be seen that an average alpha particle traversing 44.8 mm in the TEPC cavity deposits 85.11 keV. As a consequence, the lineal energy is y_α = energy deposited/mean chord length = $85.11\,\mathrm{keV}/(2/3)\,\mu\mathrm{m} = 127.67\,\mathrm{keV}/\mu\mathrm{m}$. The calibration of lineal energy y_I with channel I in the MTE-filled TEPC is thus given by,

$$y_I = \frac{127.67\,\mathrm{keV}/\mu\mathrm{m}}{I_\alpha} \times I, \tag{4}$$

where I_α is the channel number corresponding to the alpha peak of ^{241}Am. In the calibration, counting rate of the TEPC to the built-in ^{241}Am alpha source is about 1.2 cps. For an accurate I_α value, the data collection time should be no less than 20 min. At bias of 730 V, the lineal energy per channel using Eq. (4) was 0.152 keV/μm. With an MCA of 2048 channels, the measured lineal energy can be extended from 0.2 keV/μm to 300.0 keV/μm in a single measurement. The measured alpha peak with TEPC biased at 730 V is shown in Fig. 6.

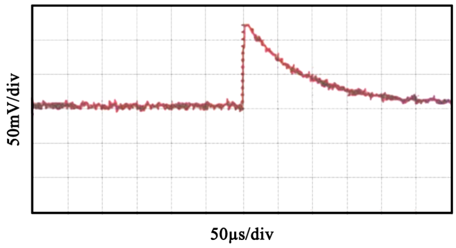

Fig. 4. (Color online) Output signal of pre-amplifier for ^{241}Am alpha source.

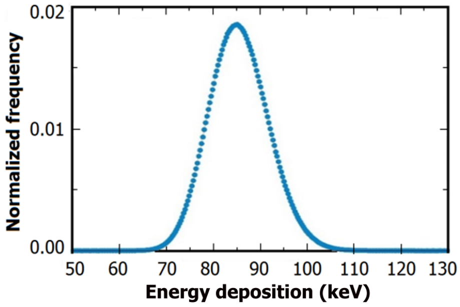

Fig. 5. (Color online) Energy deposition of ^{241}Am alpha particles in TEPC simulated by FLUKA code.

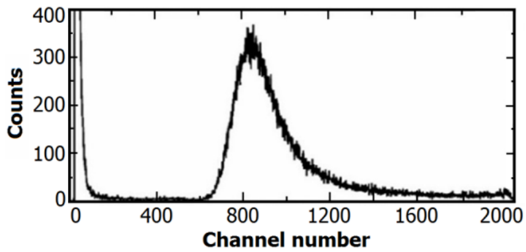

Fig. 6. (Color online) Alpha peak measured by TEPC biased at 730 V for detector calibration.

B. Dose equivalent response of the TEPC in ^{252}Cf neutron field

The direct output of TEPC measurement is pulse height distribution, which is known also as energy deposition spectra. The TEPC measurement of a ^{252}Cf source is shown in Fig. 7. After photo components [16] of ^{252}Cf source and electronic noise subtraction, the lineal energy y_i and counts n_i for each channel were calculated using Eq. (4). Absorbed dose D, mean quality factor Q and dose equivalent rate were derived using Eqs. (1)–(3). Thus, measured from the ^{252}Cf source, we had H_{TEPC} rate $=$ 19.2 µSv/h and H*(10) rate = 17.6 µSv/h. It should be noted that the reference value of H*(10) rate for ^{252}Cf neutrons at the same point was 17.6 µSv/h, so that the dose response of the TEPC to ^{252}Cf neutrons is $R_H = 1.1$, indicating a good approximation of dose equivalent rate reading of the TEPC to H*(10) rate in ^{252}Cf reference neutron fields.

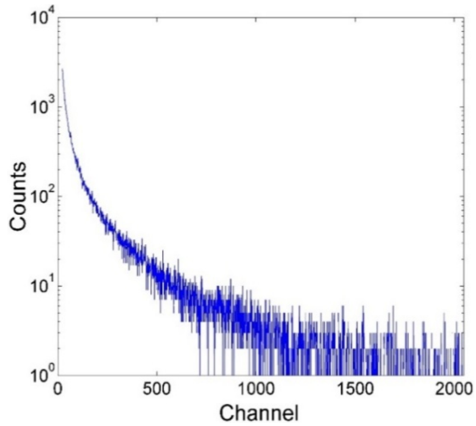

Fig. 7. (Color online) Pulse height distribution of ^{252}Cf neutrons measured by TEPC.

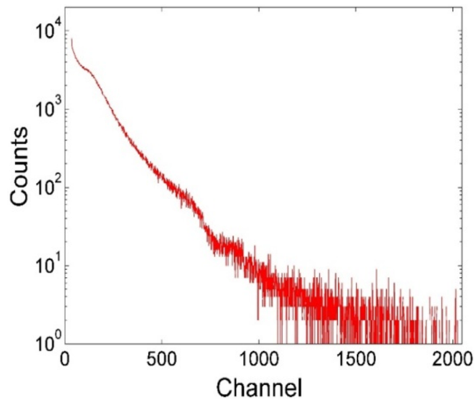

Fig. 8. (Color online) Pulse height distribution of 2.45MeV neutrons measured by TEPC.

C. Characterization of TEPC in mono-energetic neutron field

1. *Microdosimetric spectra and mean lineal energy*

Figure 8 shows the measured pulse height distribution of 2.45 MeV neutrons. Frequency-mean lineal energy $\bar{y}_f$ and dose-average lineal energy $\bar{y}_d$ were estimated from the measurement using Eqs. (5) and (6),

$$\bar{y}_f = \frac{\sum_{i=1}^{N} y_i \times f(y_i)}{\sum_{i=1}^{N} f(y_i)}, \tag{5}$$

$$\bar{y}_d = \frac{\sum_{i=1}^{N} y_i \times d(y_i)}{\sum_{i=1}^{N} d(y_i)}, \tag{6}$$

where, $f(y)$ is the probability density function of lineal energy:

$$f(y_i) = \frac{n_i}{\sum_{i=1}^{N} n_i}, \tag{7}$$

$d(y)$ is the dose distribution:

$$d(y) = y \times f(y). \tag{8}$$

TABLE 1. Experimental and simulated mean lineal energy of 2.45 MeV neutrons

	Measured data	FLUKA
y_f (keV/µm)	28.9	31.7
y_d (keV/µm)	50.8	47.5

The measured and simulated mean lineal energy are given in Table 1. In general, the measurement results agree well with the simulation results, being just 8.8% less than the simulated $\bar{y}_f$ and 6.9% larger than the simulated $\bar{y}_d$. The measured and simulated microdosimetric spectra are shown in Fig. 9. It can be seen that the two spectra fitted well to each other for the region of >40 keV/µm, though they differ relatively large in the region of <10 keV/µm, probably due to the photo events, which was omitted in the FLUKA simulation. The falling slope near 100 keV/µm, referred as the proton edge, was attributed to the recoil protons generated in the A-150 plastics and stopped exactly at the border of A-150 and MTE gas after traversing a random diameter of the cavity. Because of the Bragg effect, the recoil protons deposited the maximum energy. According to energy-range relations for protons in MTE gas, the proton energy was 72.6 keV for TEPC simulating 1 µm tissue. The corresponding lineal energy was 108.9 keV/µm, which agreed well with both the experimental and simulation results.

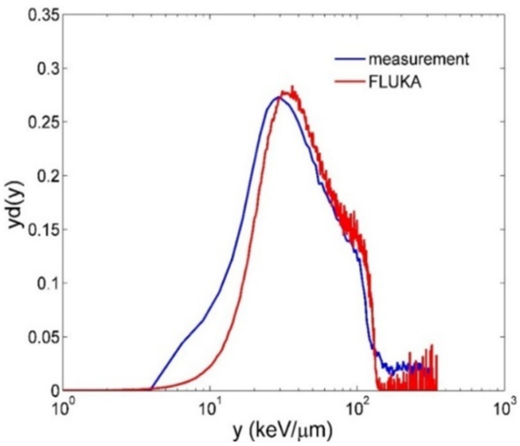

Fig. 9. (Color online) Microdosimetric spectra for 2.45 MeV neutron.

2. *Mean quality factor and dose equivalent*

Absorbed dose D of 2.45 MeV neutrons to the TEPC was estimated at 1.9 mGy using Eq. (2). The mean quality factor was evaluated using Eq. (3) and compared with the effective quality factor [17] $Q_{\rm eff}$. The measured dose equivalent was obtained using Eq. (1), ambient dose equivalent $H^*(10)$ estimated by employing fluence to $H^*(10)$ conversion coefficient [18] was used for comparison. All the results are listed in Table 2. For mean quality factor, evaluated value from measurement underestimated the $Q_{\rm eff}$ by 21.8%, this is mainly attributed to the approximation of LET by y. Operation of the TEPC in lower pressure with a simulated size of 0.5 µm or less may alleviate this problem. For dose equivalent values, the difference between the results was 1.66%.

TABLE 2. Experimental and simulated mean lineal energy of 2.45 MeV neutrons

	Q	H (mSv)
Measured data	9.7	18.4
Reference data	12.4	18.1
Relative deviation	21.8%	1.66%

IV. CONCLUSION

We have developed a spherical TEPC that used as a neutron dosimeter for radiation protection purpose. Benjamin design was employed to improve the energy resolution of the TEPC. The measured lineal energy of the TEPC can be extended from 0.2 keV/µm to 300 keV/µm in a single measurement when biased at 730 V. The dose equivalent response of the TEPC was found to be 1.1 in the ^{252}Cf reference field. Microdosimetric spectra, frequency mean lineal energy and dose-average lineal energy of 2.45 MeV neutrons have been evaluated and showed good agreement with the FLUKA simulated results. Mean quality factor and dose equivalent H estimated from measurement agreed well with the reference data.

Preliminary results have indicated that the developed TEPC had sufficient accuracy to measure lineal energy distribution used for absorbed dose and mean quality factor estimation. The evaluated dose equivalent can be used to approximate $H^*(10)$ for neutron radiation protection. Further characterization of the TEPC in low neutron fields around nuclear reactors are in progress.

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